Robotic Infrastructure for Mars Outpost Water Supply

Brian H. Wilcox
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4625
Brian.H.Wilcox@jpl.nasa.gov

A. Scott Howe
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4492
Scott.Howe@jpl.nasa.gov

Abstract— Intercontinental rovers servicing automated solar-powered Rodriguez Wells can supply water for Human Exploration on Mars. This paper describes a solar-powered multi-vehicle concept that can turn water resources obtained from mid-latitude glacier ice into a sustained water supply. A robotic drilling platform is proposed that can access relatively pure water ice in mid-latitude Martian glaciers through 1-10m of loose regolith, whereupon long-distance tanker rovers continually traverse terrain between the drilling operation and human outposts located in Mars equatorial zones. Robotically deployed solar-thermal panels will be able to passively heat warm water that is delivered into a Rodriguez Well (a melted cavity in an expanse of water ice such as a glacier). Newly melted water will be pumped up out of the well and cycled through the solar panels to fill tankers. The tankers will consist of multiple four-wheeled linked cars in a tram-like configuration that can overcome steep terrain and obstacles. The system will be able to deliver its own landed mass of water to the human explorers every ~74 Mars days. The resources, power, vehicle configurations, and detailed functions are described.

TABLE OF CONTENTS

978-1-5386-2014-4/18/$31.00 ©2018 IEEE

1. INTRODUCTION

It has long been recognized that Human exploration of Mars would be facilitated if in-situ resources could be harvested to assist with, especially, life support, ascent propulsion, and radiation shielding, not necessarily in that order of priority. While some effort has gone into studying extraction of CO_2 from the atmosphere as a raw material for these purposes, the low density of the Mars atmosphere (about 0.5% that of Earth) makes this difficult.

Water is another resource that could be the raw material for all of these high-priority applications. It has long been known to exist in a permanent ice cap at the South Pole, and orbital neutron spectrometer data has suggested and the Phoenix lander confirmed readings indicating high concentrations of water ice exist just below the surface in the high latitudes of both hemispheres. The SHARAD orbiting radar has detected many examples of what appear to be ancient glaciers in the mid-latitudes (above ~40^o N or S) that are hundreds of meters thick, evidently composed of nearly pure water ice, covered by less than 10 m of loose regolith.

Studies of Human exploration of Mars generally assume that initial exploration will focus on the equatorial zone, since the thermal environment, difficult even at the equator, becomes increasingly challenging at higher latitudes. The tilt of Mars' axis (25.2^o versus 23.4^o for Earth) makes the seasons slightly more extreme than on Earth as one approaches the poles. If human astronauts were required to be co-located with a water-extraction-system at ~40^o latitude, the sun would only get ~15^o above the horizon in the winter, and the days would be very short. Even at the summer solstice, the sun would only deliver ~90% as much power on a clear day as at the subsolar point, dropping to 26% at the winter solstice.

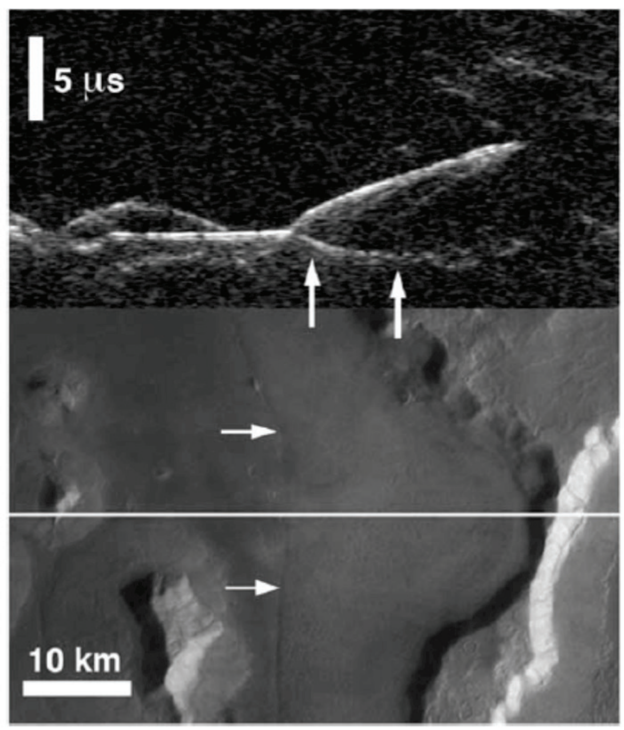
Also, there is no reason to believe that the ideal locations for the extraction of a water resource will also be the most scientifically interesting places for human exploration. Indeed, "exploration without mobility" is almost a contradiction in terms. The ideal human exploration strategy would call for humans to be able to explore across a range of widely-separated sites, if not during a single mission then at least on consecutive missions. This becomes possible if re-usable infrastructure is mobile and can "meet" each new crew at new sites when they arrive. Making infrastructure mobile is relatively attractive in a low-gravity environment, since both the mass and power required for a mobility subsystem at a given payload mass scales with gravity.[1] On Earth, it is common for off-road vehicles to have a payload approximately equal to or greater than their own mass. In the low gravity of Mars, we can expect similar vehicles to have payloads almost three times their own mass.

Thus we have a question: is it possible to create a relatively low-cost system that is capable of robotically extracting resources from buried water ice deposits at ~40° latitude and robotically transporting those resources to human exploration site(s) in the equatorial zone? The purpose of this paper is to elaborate possible details of such a system.

2. The Resource

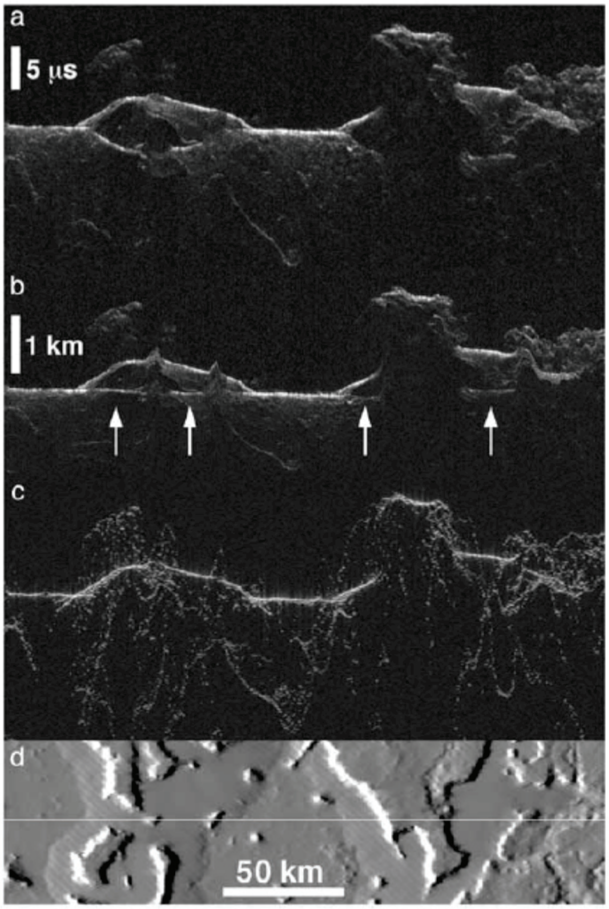
We first review the evidence that ancient glaciers offer a resource of nearly pure ice in the mid-latitudes. This evidence, shown in Figures 1 and 2, comes from the SHARAD radar orbiting Mars as described by Plaut et al.[2] Figure 1 here combines their Figures 2 and 3 from this reference. In these figures, the radar return from the SHARAD radar is shown along the top as it scans along the orbital track from left to right, with a photo of the corresponding terrain shown just below with the track line identified. In the bottom figure the radar time delay is corrected by assuming the dielectric properties of pure ice in computing the delay between the initial surface reflection and the reflection associated with the buried base of the apron. With this assumption, the base of the apron is revealed to be coplanar with the adjacent valley floor, giving credence to the idea that the apron is composed of nearly pure ice.

This evidence, along with the morphology of these deposits, suggests that the lobate debris aprons which are common on Mars at >40° North or South latitude are ancient glaciers which remain from the last glacial period. As described in Plaut et al, the surface of these ice deposits are thought to be covered with less than 10 meters of loose regolith (e.g. less than the time-resolution of



(top) SHARAD radargram and (bottom) High Resolution Stereo Camera [*Neukum et al.*, 2004] image along the groundtrack (white centerline) of lobate debris aprons in Deuteronilus Mensae. Vertical dimension of the radargram is time delay. Arrows in the lower panel indicate the distal margin of the lobate debris apron. Arrows in the upper panel indicate subsurface detections interpreted to be the lower boundary of the apron material. A smaller apron on the left shows echoes from the surface of the apron, the surrounding plain, and the buried base of the apron. SHARAD observation 214501. Center: 42.1°N, 18.5°E. North is to the right.

Figure 1: Evidence for Mars water ice at mid-latitudes (Plaut et al. 2009)



SHARAD radargrams, (a) with the vertical dimension in time delay and (b) with the vertical dimension converted to depth assuming a subsurface dielectric constant of water ice (3.2). Arrows indicate subsurface reflections that are closely coplanar with the adjacent valley floor in the depth-corrected radargram. (c) Simulated radargram showing the expected positions of off-nadir topographic clutter echoes. (d) MOLA topography along the ground track. SHARAD observation 719502. Center: 39.1°N, 24.2°E. North is to the right.

Figure 2. Further evidence of water ice in Lobate Debris Aprons on Mars (Plaut et al 2009)

the SHARAD radar can resolve). Note that the thickness of the ice deposits is typically hundreds of meters and can reach a kilometer or more.

Figure 3 shows further evidence that these deposits are nearly pure ice, showing that a fresh crater in the overburden reveals a bright white surface underneath.[3] That white surface was spectroscopically identified as water ice using the CRISM instrument.

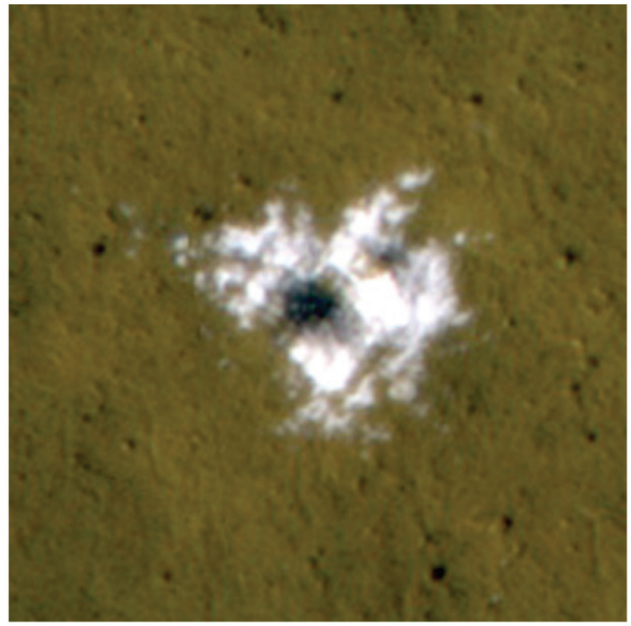


Figure 3: Fresh water ice exposed by new crater on Lobate Debris Apron that formed between January and September 2008. The ice was identified spectroscopically using the CRISM instrument.

3. POWER

Solar power is the obvious first choice for this system, because of its simplicity, if it can be made to work. The other alternative, some form of nuclear power, has difficulties related to launch approval, cost, and public support. So we first examine solar power as an option. Figure 4 shows the average energy available from solar power as a function of latitude and season on a typical Mars day (not during a dust storm).[4] One Mars day is called a sol, which is 1.026 days. The plot is not symmetric between North and South due to the elliptical nature of Mars' orbit around the sun.

We see that an installation at ~40°N latitude has over 3000 Wh/m^2/sol available over 60% of the year, with over ~2000 Wh/m^2/sol available the remainder of the year. Major dust storms occur near perihelion, when it is winter in the northern hemisphere. Only ~10 global dust storms have occurred in the ~50 Mars years that scientists have been observing Mars, so they don't happen every perihelion.[5] But when they do, the equipment will need to "hibernate" for some time in the northern winter, when solar power is already scarce. So hibernation in some form already is a required part of the design, since full operation using solar power in the winter is not possible under the best of conditions.

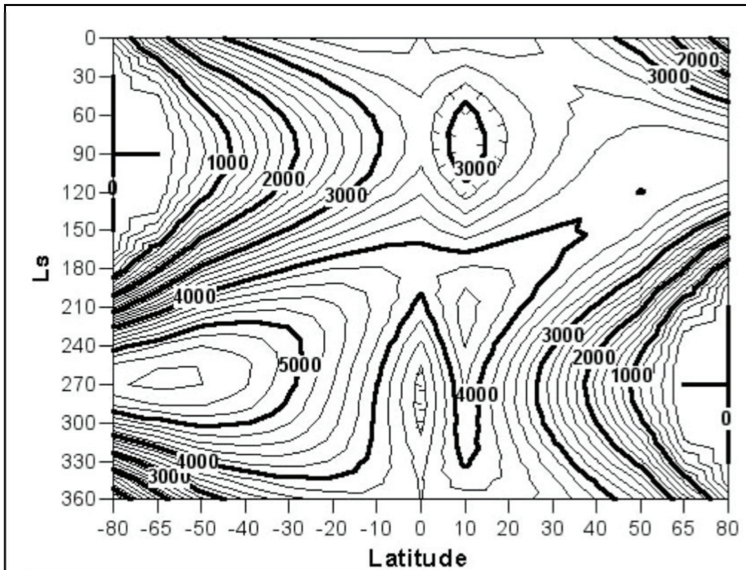


Figure 4: Plot of Wh/m^2/sol of solar power available on Mars during a typical (non dust storm) day as function of latitude and season. Daily total solar intensity on an equator-facing slope = 20^o at an optical depth = 0.5. Note that, for ~40^{o}N latitude, a minimum of ~1800 Wh/m^2/sol is available, with over 3000 Wh/m^2/day for ~60% of the year. (Rapp, 2007)

A "Rodriquez Well" (or Rodwell for short) is a heat source embedded in an expanse of ice that melts a "bulb" of water than can be pumped out at a rate appropriate for the amount of heat supplied. The use of Rodwells as a source of water is well established in terrestrial arctic and Antarctic exploration, and their possible application to Mars is well described by Hoffman et al.[6] They consider the case where it is desired to produce 100 gallons of water per sol (1 gallon = 3.785 kg), similar to the use rate for a terrestrial household. Figure 5 shows the cumulative water produced by such a well versus time for different levels of power provided in the form of heat down the well. At the lower right in Fig. 5 is a cartoon of the Rodwell configuration. For heat inputs greater than 20 kW (continuous), the amount of water retained in the downhole bulb grows rapidly. At 20 kW heat input, over the long-term most of the water is produced out of the well. At 10 kW, the water retained in the bulb stabilizes at about 20 metric

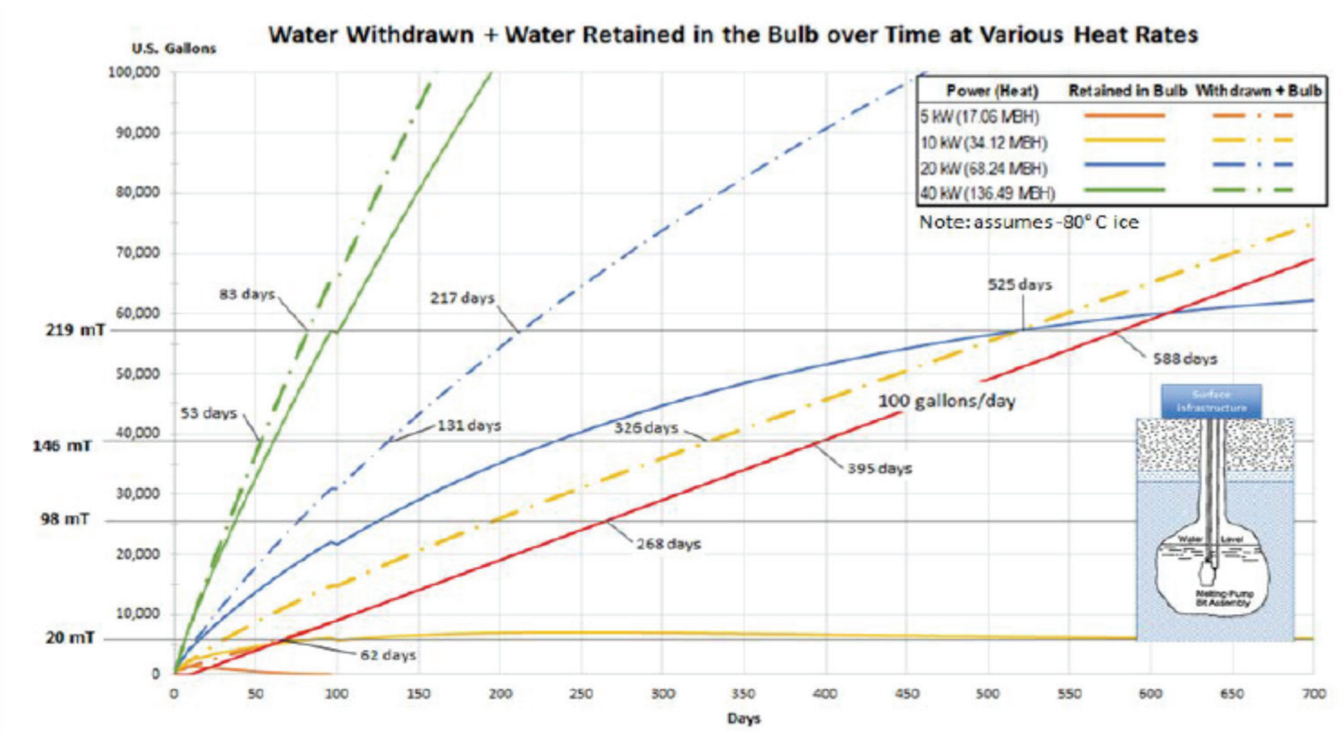


Figure 5: Water withdrawn from Rodriguez Well at 100 gal/day (Hoffman et al, 2017)

tons. At 5 kW, the rate of withdrawal of 100 gallons per sol causes "well collapse" where not enough water remains in the bulb to accomplish heat transfer to the ice, and continued pumping extracts all the water.

We hence consider the case where we provide 10 kW continuous, or 240 kWh per sol, of heat into the Rodwell at ~40^{o}N latitude and our transport system moves 100 gallons per sol of water to the human explorers in the equatorial zone.

We see from Figure 4 that, except for a brief period, at least 2000 Wh/m^2/sol will be available and hence we will need 120 m^2 of solar heat-collecting panels to get 240 kWh per sol, even if the panels and associated systems were 100% efficient in harvesting solar power and delivering it into the Rodwell. Figure 6 shows the rate of passive convective heat transport in W/m^2/C from a horizontal cylinder as a function of gas pressure.[7] (This data is for air; the CO_2 on Mars has a higher molecular weight and therefore would be expected to be somewhat less efficient at convective transport.) We see that, at 40^{o}C, all the curves at different pressures are dropping rapidly in terms of heat transport coefficient. At Mars pressure, which is approximately at the logarithmic mean between the two lowest curves plotted, we expect convective heat transport to extract about 2 W/m^2/C from hot panels exposed to the Mars atmosphere. Since the temperature of the atmosphere will be well below 0^{o}C in most cases, with the panel interior heated to >40^{o}C, we can thus expect a heat loss of ~100W/m^2 from each side of each panel. This represents a significant fraction of the total insolation at Mars (typically less than 500 W/m^2). So it is not advisable to have the bare sunlight-absorbing panels exposed to the Mars atmosphere.

Fortunately, the pressure on Mars is so low that the mechanical penalty for enclosing the panels in a vacuum jacket is not problematic. On Earth, such vacuum-jacket absorbers (often in the shape of cylinders at the focus of linear parabolic reflectors) are used whenever efficient, high temperature solar thermal collection is desired. Selective-absorber surfaces, which can absorb ~95% of the visible light while having a thermal emissivity of only 5%, allow high temperatures to be generated. Glass sheets can provide the vacuum enclosure, and because the Mars atmospheric pressure is so low, only handling considerations dictate the thickness of the glass. Water circulating through the selective-absorber panels can absorb solar power at, say, 40^{o}C so there is adequate ΔT between the water and the ice in the Rodwell, without excessive heat loss at the panels. The overall thermal efficiency of such a system could presumably be ~80-90% without great difficulty.

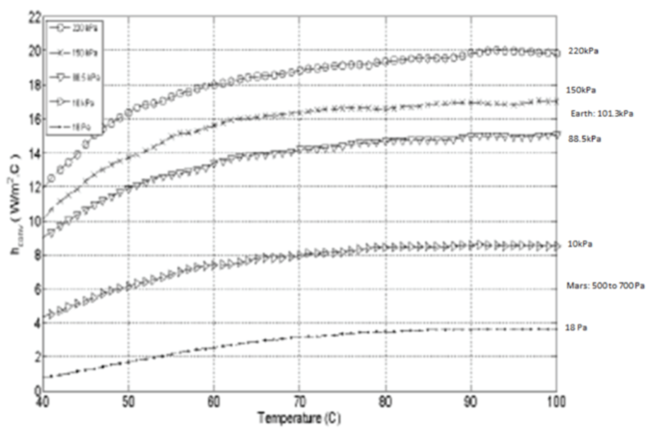


Figure 6: Convection heat transfer coefficient with temperature at different pressures (Saidi et al 2010)

When the sun goes down, and during hibernation in the depths of winter or during dust storms, the water would be allowed to drain out of the panels so it doesn't freeze inside them. That water would be preserved in liquid form in the bulb of the Rodwell (see inset of Figure 4). One of the first questions is, would the water in the Rodwell freeze overnight if the only source of heat were the solar thermal panels that operate only in daylight? To answer this question we consider the heat of fusion of the liquid in the Rodwell, and compare it to the daily pulse of energy that comes in from the solar panels. As we noted, the mass of liquid in a Rodwell supplied with 240 kWh per sol of energy is about 10 tons. The heat of fusion for this water (at 333 J/g) is 3.33x10^9 Joules, which 925 kWh. Since this is comfortably larger than the 240 kWh that we supply during each sol, we conclude that the Rodwell will shrink somewhat, but not come nowhere near freezing each night.

The same cannot be said of the behavior of the system during a dust storm. Since global dust storms occur during the depths of northern winter, we may have to face weeks of very little sun. Figure 7 shows the daily solar energy falling on a horizontal panel at the peak of a Mars dust storm.[8] We see that at 40^o north latitude, during a global dust storm (L_s~270^o) the insolation on our panels may be as low as 400Wh/m^2/sol. This provides about 20% of our nominal input of 240 kWh/sol, and so on a daily average is about the same as a 2000 W continuous input.

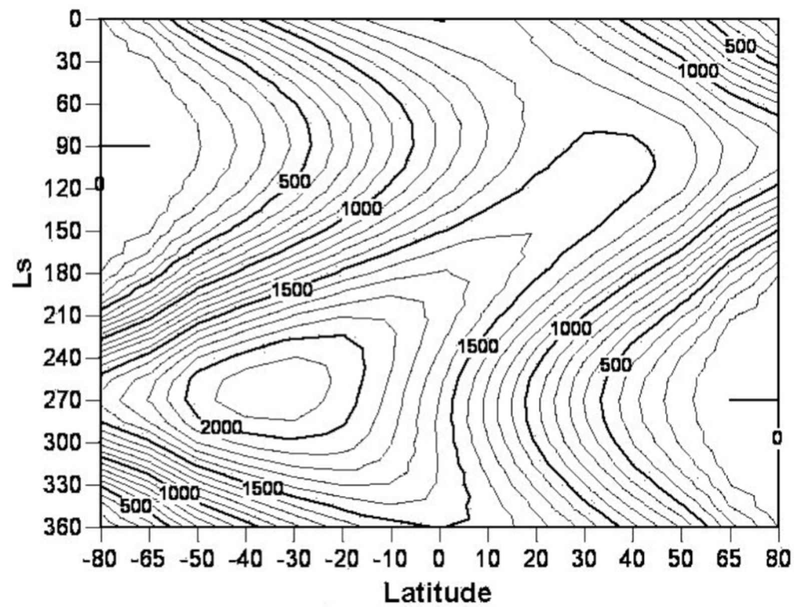


Figure 7: Daily total insolation in Watt-hours per square meter on horizontal surfaces for an optical depth = 4.0 corresponding to the peak of a global dust storm (Rapp 2007).

In Figure 5 we saw that 5000 W of continuous heat input was not sufficient to support 100 gal/sol extraction of water, but if all we wanted to do was to preserve a small liquid pool that allows circulation of water through the panels each successive day, with no net withdrawal of water, it seems that this might be possible with only 2000 W of equivalent continuous input heat. To explore this further, consider that the steady-state solution to the diffusion equation for a point source of heat in an infinite conducting medium at temperature T_0 is of the form $T(r)=T_0+P/4\pi kr$ where P is the input power and k is the thermal conductivity in W/m*K.[9] We can readily confirm this is the solution by differentiating both sides with respect to r, getting $P=-4\pi r^2 k(dT/dr)$ which clearly satisfies the condition that it has the same heat flow P going out through each spherical shell at any radius.

To find the radius r_0 of the melt sphere, we set $T(r_0)=0^oC$ and use the assumption of Hoffman that the ice body is originally at -80^{o}C. So $P/4\pi kr_0=80$, or $r_0=P/320\pi k$. The value of k for pure water ice just below 0^{o}C is about 2.2 W/mK. So for P=2000W, we have r_0=0.904 m. The mass of meltwater in a sphere of radius 0.904 m is 3097 kg, which has a latent heat of fusion of 1.03×10^9 Joules. If heat leaks out at 2000 W, this bulb of water would require 143 hours to freeze, which is ~10 times longer than the winter nights at 40^{o}N latitude. So we conclude that, even in the winter during a severe global dust storm, a few tons of liquid water would remain in the bulb of the Rodwell so that each morning there is liquid that can be pumped through the solar thermal panels to regenerate the bulb for the next sol. During other parts of the year, 100 gallons of liquid water per sol can be extracted from the bulb without difficulty. Clearly there needs to be a battery which provides power for the pump to lift the required liquid through the panels in the morning, so at least part of the panel area must also be photovoltaic to provide this small amount of electric power.

4. ROBOTIC ELEMENTS

We next turn our attention to the robotic elements needed for the system. The ISRU Driller shown in Figure 8 consists of a deployable solar panel, tilt-up drill tower, and pump system on a 4-wheel mobility system. Each wheel on the mobility system has its own steerable motor, which is mounted to a 4-bar linkage suspension system.

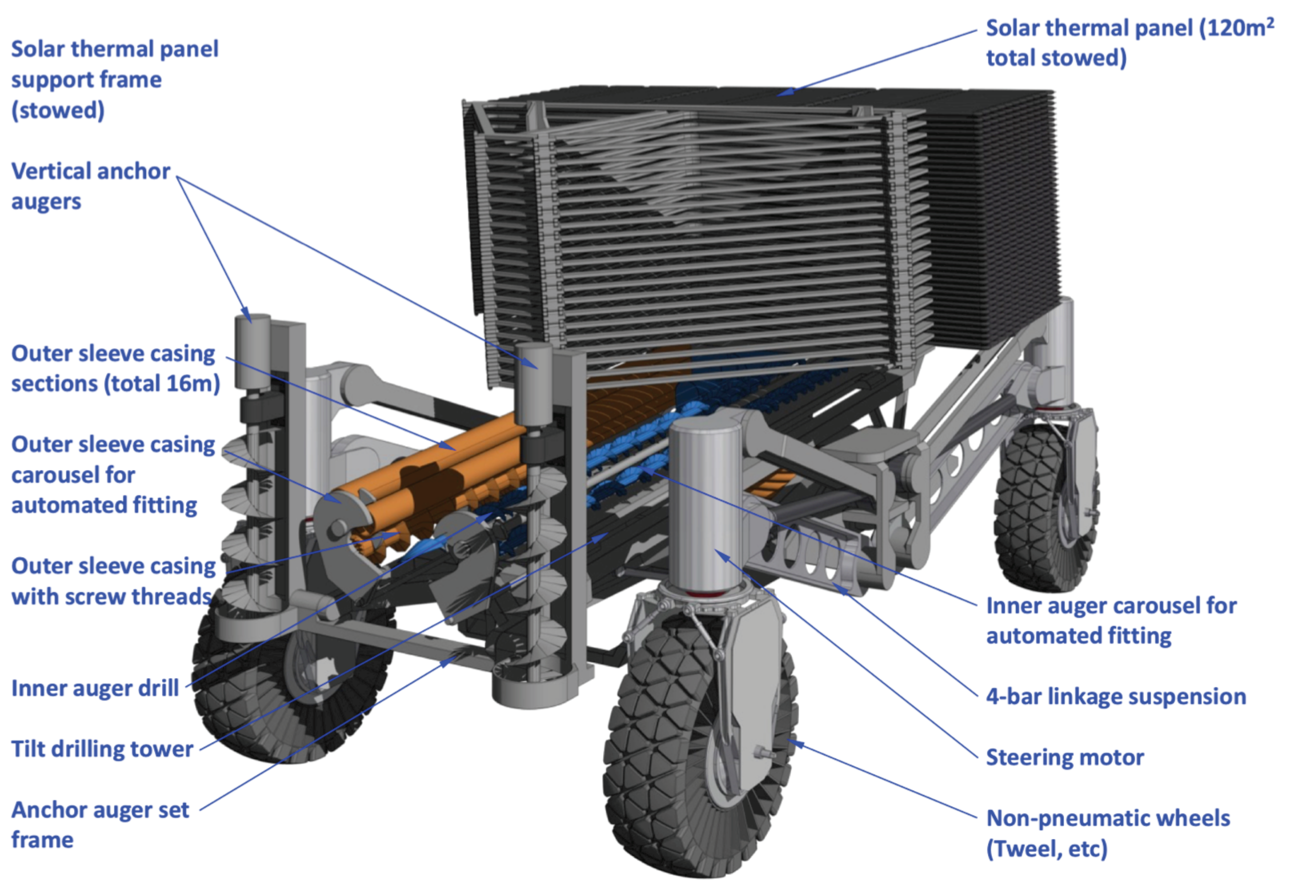


Figure 8: Drill Vehicle concept. Able to deploy ~120 m^2 of solar thermal panels and to drill through ~10 m of overburden to reach water ice and start/maintain Rodriguez Well.

Each of the 4-bar suspension assemblies can raise or lower the wheel, and can be rotated laterally to modify the stance or increase the ground contact polygon to adapt to a variety of terrain. In addition, the lateral rotation capability of each 4-bar assembly will allow the mobility system to set the chassis down on the ground and do a limited walk in case the vehicle gets stuck in sand or encounters other obstacles. The tilt-up drill tower is laid down horizontally when the vehicle is stowed or in transit, supporting the deployable solar panel in a compact package.

The ISRU Driller would have the ability to deploy and retrieve 120 m^2 of solar thermal panels that would absorb sunlight in the form of heat delivered to water circulating through the panels. Assuming that the array of panels is ~3 m tall, then we need to be able to deploy and retrieve a 40 m linear array of such panels (at 40^{o}N latitude, tilted 20^o toward the equator). The Drill Vehicle has ~10 m of pipe with an external flute that can be screwed or augered vertically into the ground over the glacier. Then a smaller internal auger bit can clean out the contents of this pipe and drill a short distance into the ice to start the Rodwell. The Rodwell itself is started by lowering a submersible pump assembly through the pipe into the ice. The Drill Vehicle will have a spool of ~30 m of hose (3-5 cm in diameter) with the pump (a cylinder ~8 cm in diameter and ~50 cm long) that it can lower through the pipe into the hole in the ice. So the Drill Vehicle needs a way to 1) screw or auger the 10-m pipe into the regolith, 2) insert the smaller internal auger into the pipe to clear debris and auger some distance into the ice at the bottom, 3) remove the auger from the pipe and send the pump on the end of the hose down. As the water is extracted from the Rodwell over many months, the spool gradually delivers all ~30 m of hose into the pipe and down into the ice. When a new Rodwell needs to be started, it spools the hose back onto the reel, and must be able to unscrew the pipe out of the

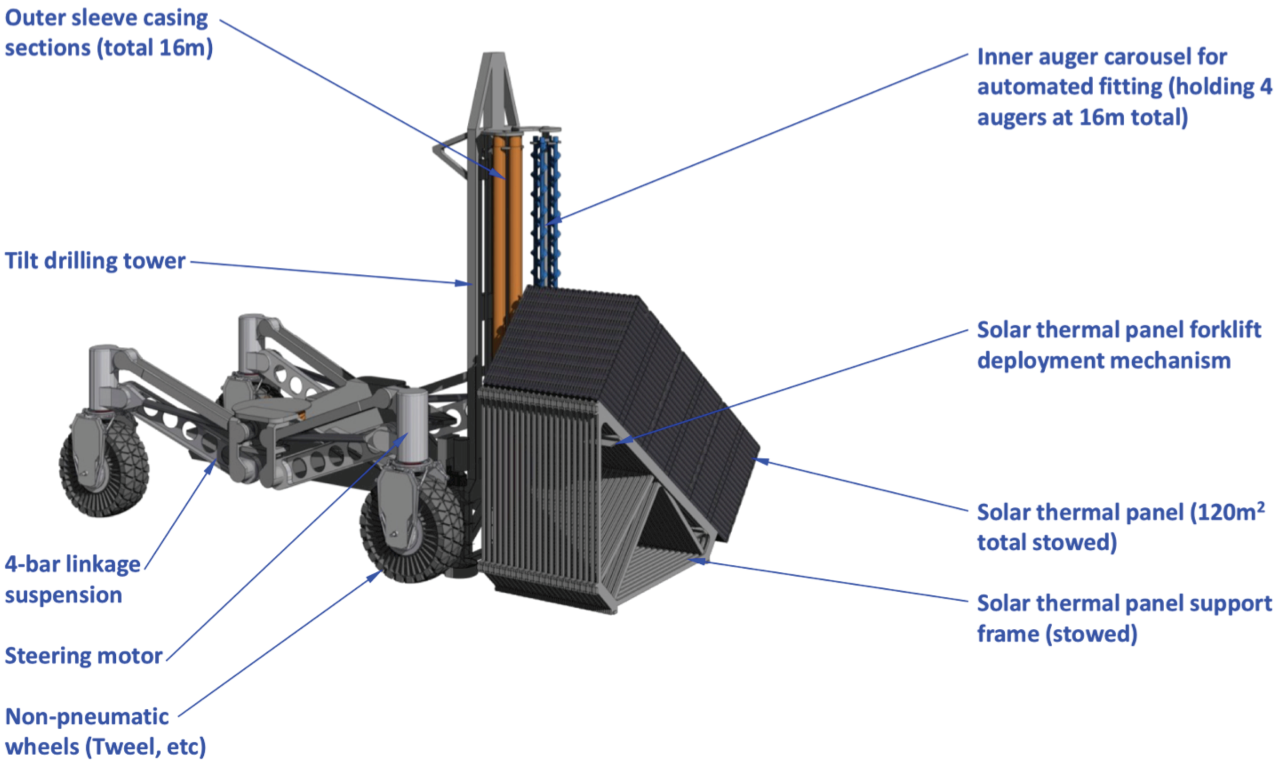


Figure 9: Drill Vehicle anchors one end of accordion solar thermal panel array to the ground.

ground. Figure 9 shows how a fork-lift deployment mechanism tilts to the proper angle as it lowers the solar panel package to the surface. The Driller would set down the solar thermal array using the tiltable drill tower as the forklift and anchors the end of the "accordion" array to the ground so that it can be pulled-out into the deployed configuration, shown in Figure 10. Placing the first solar panel frame on the surface, the ISRU Driller backs up and deploys each frame in turn until the entire $120m^2$ panel is stretched across the surface. The tilt-up drill tower in the vertical deployed configuration has two carousels that can position casings and augers into the drill motor. The right-hand carousel holds four 4m casings, and the left-hand carousel holds four 4m augers, for a total of 16m. Initially, a special casing with screw threads is drilled into the regolith until the top is level with the base of the tower. Next the starting auger is drilled down into the casing, with auger blades lifting material out of the hole. When the top of the auger has been lowered to the base of the tower, it is raised again out of the hole and placed back into the carousel. Next the second casing is mounted to the top of the first and screwed another 4m into the regolith. Using this exchange of casings and augers, in turn the driller has the capacity to drill up to 16m deep into the regolith. When all the casings are in place and into the ice, all the augers are pulled out in turn and repacked into their carousel. Finally, the pump assembly is lowered down to the ice and allowed to begin melting the melt pool.

The solar thermal panels at the Rodwell are estimated to have a mass of <30 kg per square meter (including mounting frame), so the 120 m^2 of panels required have a total mass of ~3 metric tons. A drill-augur system needed to drive and clear a liner tube to penetrate the <10 m of regolith that covers the ice might have a mass of <2 tons, so the total mass of the installed equipment at the Rodwell is ~5 tons.

As mentioned, the system is designed to produce 100 gallons per sol, for an average flow rate of 4.27 g/s. We supply >2000 Wh/sol of heat energy in the form of water heated to 40^{o}C. Assuming this energy is typically delivered over an 8-hour period each sol, the average water flow rate of the

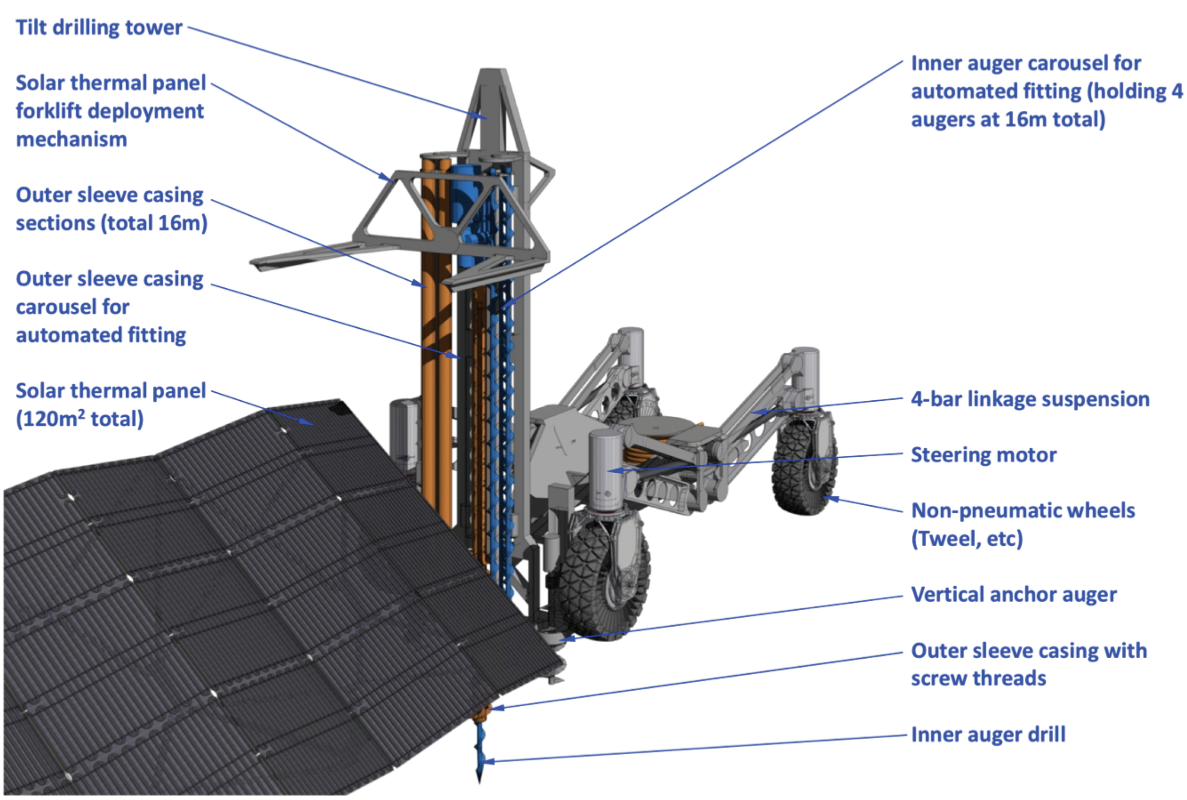


Figure 10: Drill Vehicle pulls out accordion and begins drilling Rodwell.

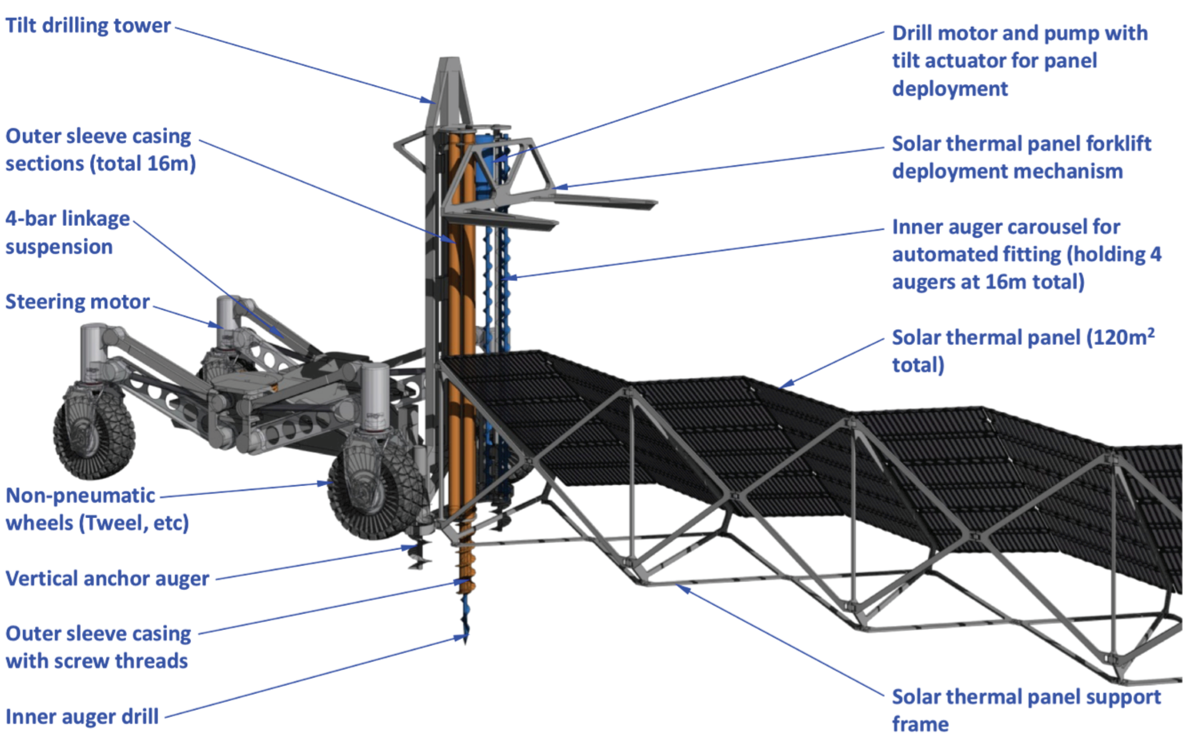


Figure 11: Internal auger is able to clean sleeve before inserting submersible pump.

hot water is 1.49 g/s. So we can imagine an insulated hose with a submersible electric pump at the bottom that supports the circulation of water through the solar thermal panels and into the Rodwell. When no transport vehicle is docked for replenishment, the water circulates during the daytime to deliver heat into the Rodwell. Presumably the hot water is released from the very bottom of the downhole assembly, so that natural convection will mix the water pool. Colder water will be drawn into the pump from higher-up the insulated hose. Before sundown the pump will be shut off and the liquid water will drain into the pool before it freezes in the panels. (A float valve at the panels can allow atmosphere to displace the water in the panels yet prevent water from escaping when the pump is turned back on in the morning.) When a vehicle arrives to take-on a new load of water, it will connect to the pressurized water coming from the pump and fill its tank over about a single daylight interval. This will be done in the daytime to reduce the risk of freezing water in the hoses. To deliver 2 tons of water in 8 hours is an average flow rate of 70 g/s, so the pump would be sized to deliver this rate. The power required to lift 70 g/s through a vertical distance of 30 m in Mars gravity is about 8 Watts, before accounting for efficiency losses. A Rodwell delivering 100 gallons/sol from a pool ~3 m in radius would descend into the ice by 1.34 cm/sol. In a Mars year the pool would descend ~9 m into the ice, so every few years the Rodwell vehicle would pull up the hose and pump assembly and move to a new site where it deploys a new Rodwell.

Next let us consider how to transport 100 gallons of water per sol from 40^{o}N latitude to the equatorial site where human exploration is taking place. A first decision is the capacity of the transport vehicle. At one extreme would be to have small vehicles, say 100 gallon capacity, departing the Rodwell once per sol. Another would be to have larger vehicles departing the Rodwell less frequently.

Figure 12 shows the published results of a parametric model comparing the payload-carrying capability of alternative vehicle configurations in Mars gravity.[10] This figure compares the 6-wheeled "Rocker Bogie" configuration of Sojourner, Spirit, Opportunity, and Curiosity with a 6-wheel-on-leg hybrid mobility configuration called ATHLETE. As one can see from Figure 10, the fraction of the total vehicle mass devoted to the mobility subsystem can be slightly lower, in this model, for the hybrid mobility configuration than for the Rocker-Bogie. Both configurations exhibit an asymptotic behavior at large total vehicle masses because the premise of this model is that the ground pressure of the wheels must be limited to prevent sinkage in soft terrain. The parametric model for the wheels and drive assemblies is such that the estimated mass of the wheels/drives at constant ground pressure become huge at very large total vehicle masses.

This model assumes that the ground pressure of the Rocker-Bogie vehicles must be limited to 1 PSI (7 kPa). The hybrid mobility system is permitted to increase this to 4 PSI (28 kPa) because it can "walk out" of any soft terrain that it inadvertently rolls into. Note that both Spirit and Opportunity, despite their ~1 PSI ground pressure, did experience difficulties with soft ground entrapment (Spirit fatally). Curiosity has also

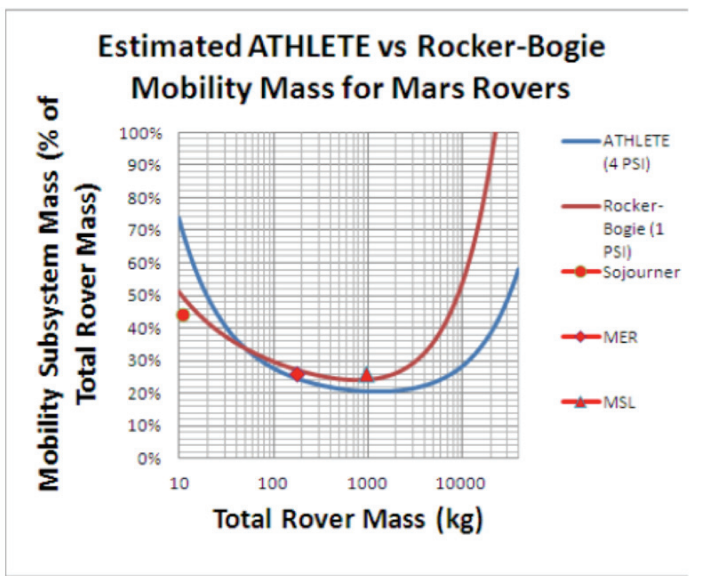


Figure 12: Parametric models of 6-wheel rocker-bogie and 6-wheel-on-leg hybrid mobility system (called ATHLETE) in Mars gravity, showing fraction of total vehicle mass devoted to the Mobility Subsystem versus total Rover Mass. (Wilcox 2013)

experienced soft ground that it had to back out of. Software was added to all three of those vehicles for "visual odometry" so that high rates of wheel slip can be detected before permanent entrapment occurs. Spirit was lost when it "broke through" a crusty layer into an unseen pit of soft material. Because the hybrid configuration has higher ground pressure than the Rocker-Bogie, the mass of these physically-large wheel/drive assemblies does not diverge at high total vehicle masses as fast as the Rocker-Bogie.

With either configuration, it is clear from Figure 10 that vehicles in the range of about one to a few metric tons can be built where the mobility subsystem is only ~20-25% of the total vehicle mass. This leaves ~75-80% for the power system, control system, payload, and support structure. At 100 gallons of water per sol, we need to move a payload of 378.5 kg/sol. Thus a reasonable sized vehicle will be able to transport from 3 to as much as 8 sols of Rodwell output.

Mobility power can be characterized as $E=\mu mgd$, where E is the bus energy required for the mobility system, μ is the "effective coefficient of rolling friction", m is the mass of the vehicle, and d is the distance travelled. Observed values of μ are given in Table 1.[11]

In the literature, the μ we have described is referred to as **Power Number**. This metric is commonly used for tractors, earth moving vehicles, etc. The Power Number is the energy used per unit vehicle weight (in the local gravity field) per unit distance.

Figure 13 is from a paper published while Sojourner was en-route to Mars[12] - giving the mean free path of a rover as a function of the rover size. This figure shows that the worst size for a rover (in terms of mean free path) in Viking Lander 2 (VL2) terrain is a length of 50 cm, not too different from the 60 cm of Sojourner. For VL1 terrain, the worst size is about 30 cm length. The issue is that small rovers can drive around obstacles and big rovers can drive over them but intermediate rovers can't do either. This is reflected in the mean-free-path of the rover being a small multiple of the rover length, which in VL2 terrain gets as low as twice the vehicle length but in VL1 terrain is over 5 times the vehicle length.

It was not known at the launch of Sojourner that most of Mars is much less rocky than VL2 terrain, or even VL1 terrain. Also, note in both charts of Figure 13 that the mean free path for vehicles more than a meter of two in length becomes large. Once the mean-free-path is many times the vehicle dimension, the paths don't become

Table 1: Rolling Friction for Planetary Rovers

Rolling Friction		μ
Sojourner		21.09
MER		2.03
MSL		1.80
Apollo Lunar rover		0.21
CMU Zoe (Atacama desert)		0.10

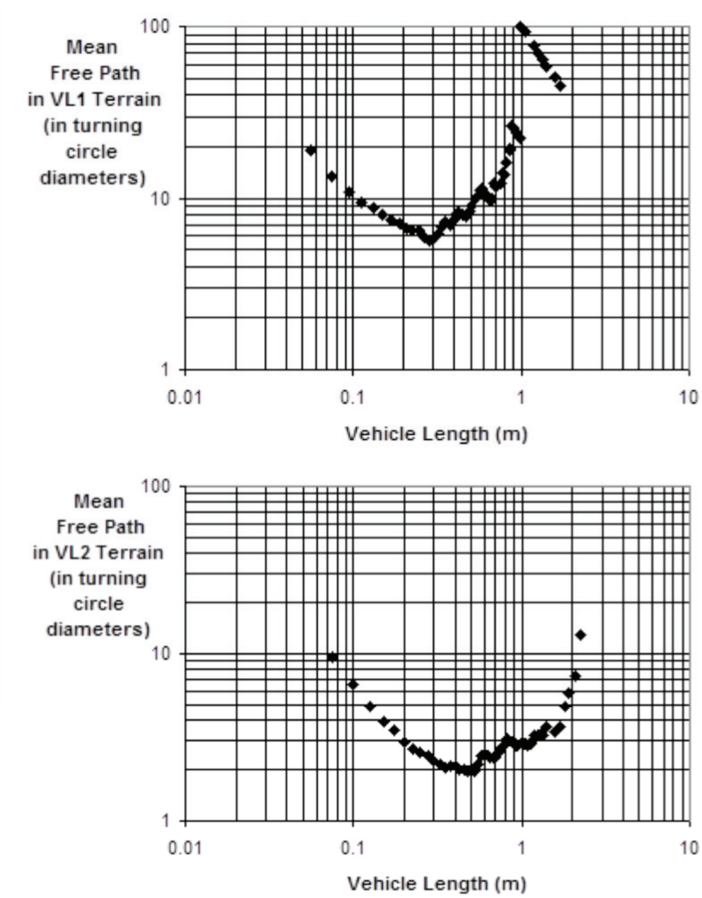


Figure 13: Mean Free Paths of Sojourner-style rovers in VL1 and VL2 terrain (Wilcox et al 1997).

torturous, there is negligible chance that back-tracking will be required, long-range sensing is not particularly valuable, and the total distance traveled is only a small multiplier over the straight-line distance from start to finish. Together, these factors make the problem of hazard avoidance and path planning almost trivial.

We conceive of a water transport vehicle as depicted in Figures 14-16. Each vehicle is a "follow the leader" tram-like configuration of cars so that it can back out of bad situations without each vehicle element having an exotic configuration. The Tanker Tram consists of linked instances of two types of vehicles: Tram Tractors and Tram Cars. Each Tanker Tram has two Tram Tractors, one in the front and another one trailing in the rear (so the vehicle is completely symmetric and reversible). Between the two tractors, up to 20 Tram Car units can be linked.

In the depiction of Figures 14-16, each of the cars has 4-wheel drive and 4-wheel steering, along with a simple passive degree-of-freedom between the right and left sides to ensure that all wheels carry approximately the same weight, that the pitch of the main car structure is the average of the pitch of the two sides, with a four-bar linkage ensuring that all the steering axes remain approximately vertical. All wheels are driven with motors inside the hubs. It is possible that this configuration may be simplified, although previous experiments with long "land trains" that attempted to use passive articulations to ensure precise follow-the-leader steering in natural terrain were unsuccessful, leading to a need for each car in the train to have individual steering.[13] The cars as shown in Figure 14 are each capable

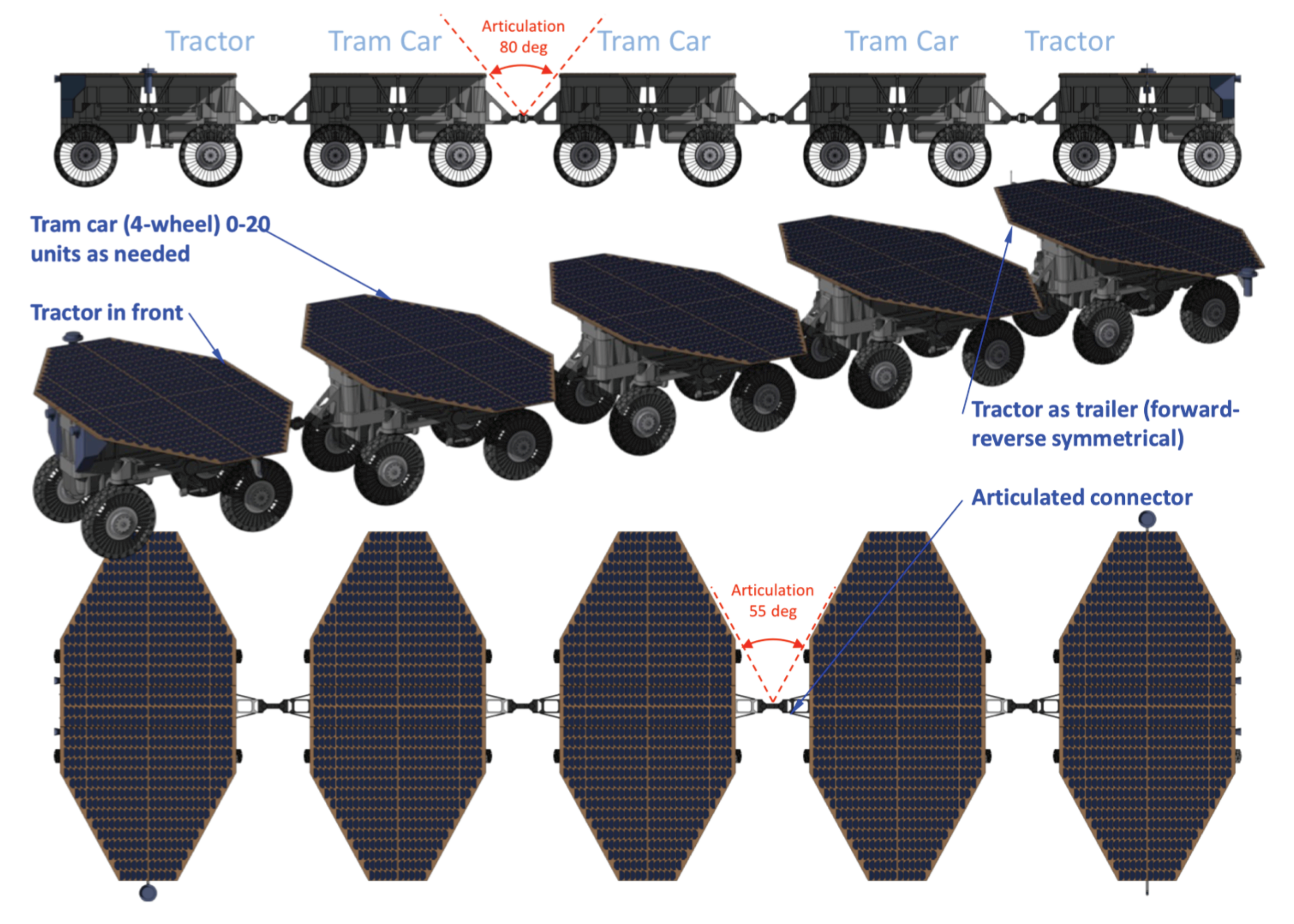


Figure 14: Configuration of "Tram" Vehicle

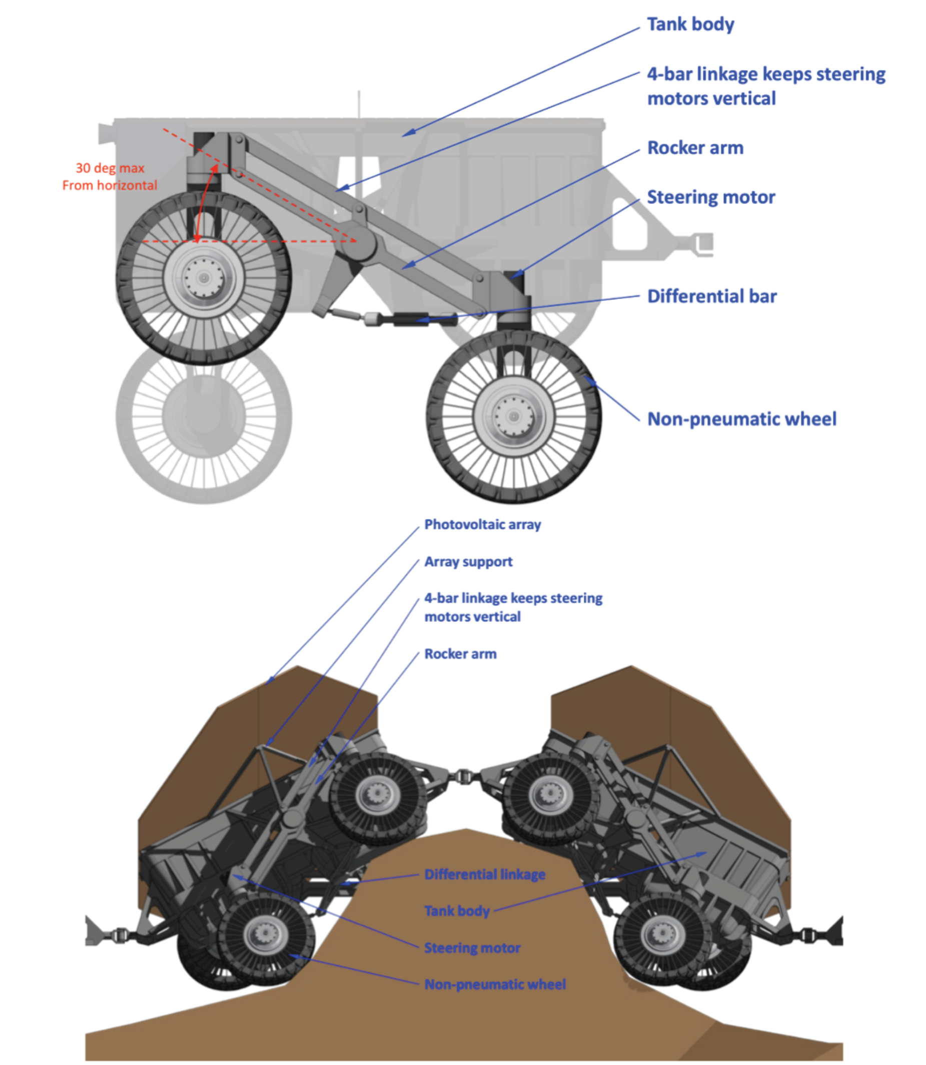


Figure 15: Detail of Tram Cars.

of being the front or rear of the train as well as being intermediate cars. We depict a detachable sensor and telemetry package at the front and back of the vehicle, attached to the end-cars which are otherwise identical to all the others. Since the mass and cost of the necessary cameras and other sensors and computing elements is trending toward zero, it is possible that all cars would or should be so equipped, with a decision on the final implementation made at the time a point-design is contemplated for flight.

Using Hofmann's assumption that the Rodwell produces 100 gallons of water per sol, this is 378.5 kg of water, produced only in the daytime since all the plumbing is drained each sol after sundown. Hence the natural size of the tank in each Tram Car is any integer multiple of 378.5 kg, so that it can be filled in the daytime and then permitted to freeze solid starting that night. Each Tanker Tram thus carries an integer number of sols of water production between the Rodwell and the human exploration site. When the Tanker Tram reaches the human exploration site, the ice can be removed from each tanker as a block of ice by flipping the top of the solar panel to remove the wedge-shaped blocks from the tapered volume.

Articulation between Tram Cars have +80 to -60 degree articulation in pitch, and also 55 degrees articulation in yaw. The Tram Tanker is capable of ~60 degrees in roll articulation between cars, but care would have to be taken to not exceed the ability of each four-wheel unit to support its own center of gravity between its own wheels. Multiple units are capable of serpentine steering articulation with an inner wheel turning radius of 1.6 m, and an outer turning radius of 2.4 m. The front Tram Car has an approach angle of 90 degrees (and the rear-facing Car has a departure angle of 90 degrees), with each Car having 0.31 m of clearance on level ground and a breakover angle of 78 degrees.

With this configuration, it is expected to be possible to overcome steep slopes, boulders, or small outcrops by using the rear cars to push the front cars into the obstacle to augment the traction from their own thrust. Once the front cars have passed over the obstacle, the front cars can then pull the rear cars following, overcoming any lack of traction.

To achieve the needed traverse rate of ~50 km/sol, we need to have the power-to-weight ratio of the entire vehicle reach the level needed for whatever Power Number we expect to achieve on natural Mars terrain. For this paper, we estimate that the power number we can achieve (see Table 1 and associated discussion in text) is 0.15. With the planned solar panel area for each tram car as depicted in Figures 14-16 of 3.13 m^2, the allowable mass per tram car is just over 300 kg (assuming 3000 $Wh/m^2/sol$ and an effective panel efficiency of 25%). Given the relative simplicity of each tram car (mostly passive articulations) it seems that over half the total mass of each tram car can be devoted to the water payload. Recall that we wanted each tram to carry an integer multiple of 100 gal/sol. Half of 100 gallons of water is 189.25 kg, which would be 62% of the maximum permissible mass if the tram is to achieve 50 km/sol in average traverse. (Of course on the return trip, when the water tanks are empty, the vehicle should be able to move much faster.) If we make the design decision that the tram would not move at night, it would not need large batteries. So it would move up to 10 km/h (a brisk walking speed) when the sun is high in the sky, and then park between late afternoon and mid-morning. Presumably it would pick a spot to park somewhere such that it will get good morning sun on the panels to start-up the next day. Traverse routes may be chosen such that the average tilt during morning and afternoon hours improves the overall energy input.

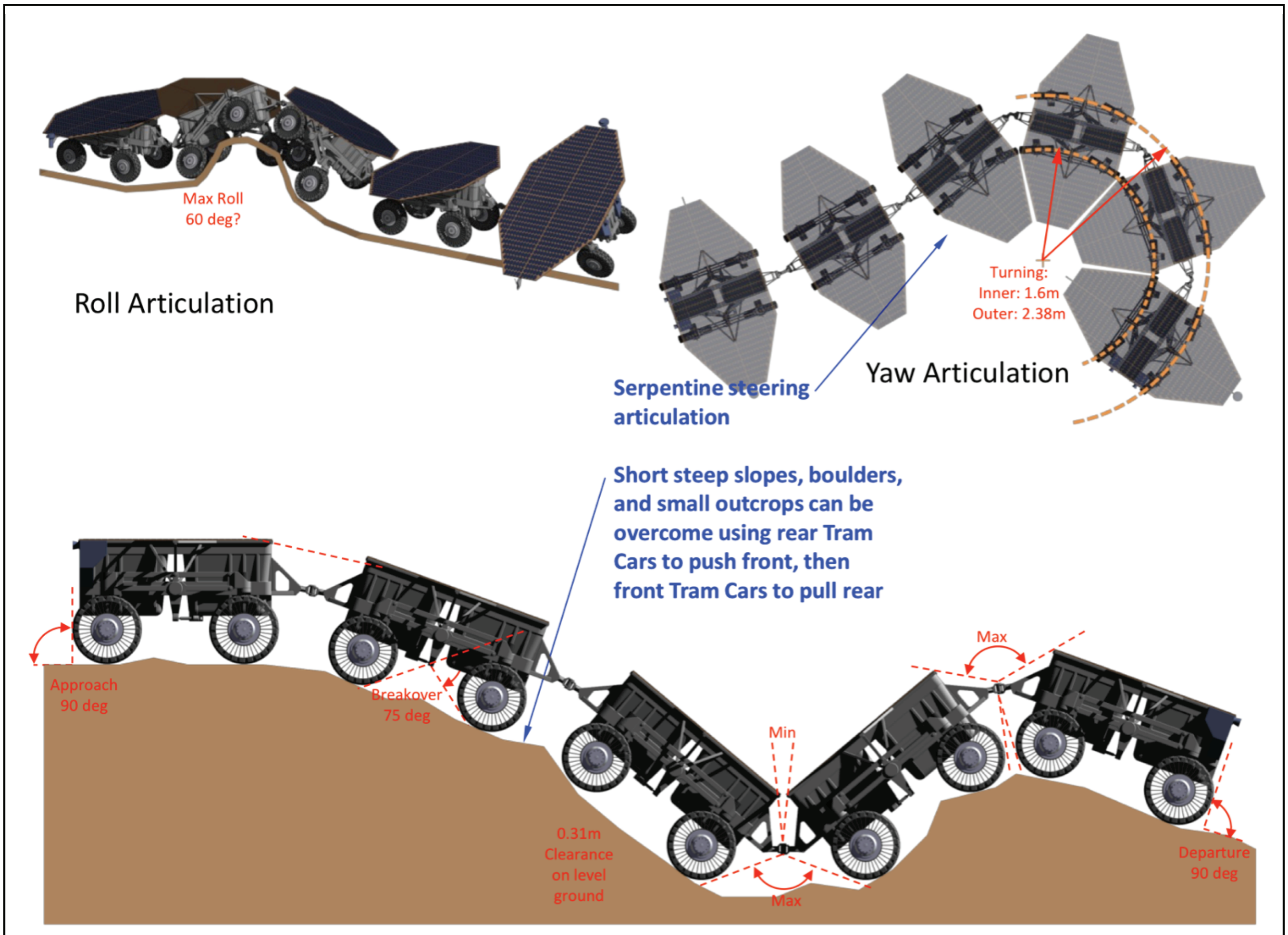


Figure 16: Tram Vehicle traversing natural terrain.

Since the human exploration site is assumed to be fixed for long periods of time (and then perhaps for all the infrastructure to robotically move to a new exploration site, such as between crews), the route from the Rodwell site and the human exploration site can be well reconnoitered and then used with little or no variation for many cycles of tram vehicle traverse. If or when the infrastructure equipment moves robotically to a new site, presumably that traverse will also be well-reconnoitered to be favorable. It seems likely that a series of human exploration sites can be arranged in relation to a single Rodwell site such that the tram vehicles can move water a minimum distance to a first site, and then somewhat further for the next site, and so on, all over well-characterized routes. Additional tram vehicles could be brought to Mars when it is envisioned to move the human exploration site to support the extra round-trip time each tram vehicle would take to go the farther distance, or to increase the average amount of water being brought to the human explorers each sol.

5. Summary and Conclusions

The evidence indicates that there is abundant, nearly pure water ice in Lobate Debris Aprons at ~40 degrees latitude, covered by <10 m of loose regolith. This water ice can be extracted as liquid water by melting a bulb of water in the ice expanse, a Rodriguez Well, in a manner similar to the use of such wells in polar exploration on Earth.

We have shown concepts for a robotic system consisting of two types of vehicles to exploit this resource to provide 100 gallons of water per sol to the human exploration site (presumed to be in the equatorial region). One vehicle establishes and maintains a Rodriquez Well, moving and re-establishing it whenever the old cavity becomes too deep. The other vehicle type is a tram-style follow-the-leader assemblage of identical tram cars, taking advantage of the fact that, if the front car or two gets into trouble, the others can pull them out. Each tram car is fore-and-aft symmetric, so the entire vehicle is fully reversible, and the only distinction between cars is that the front and back cars have an add-on sensing, computing, and telemetry package. Each tram car is optimized so that its fully-loaded range under solar power is approximately 50 km per sol in typical Mars atmospheric conditions, moving only in daytime, so that heavy batteries are not needed. In this way, it is envisioned that each tram can deliver multiple sols of water (as blocks of ice) to the human exploration site, with enough trams in transit to provide the assumed requirement of 100 gallons of water per sol.

Each tram car in this notional design has a dry mass of 114 kg and carries 50 gallons of water that soon freezes to ice. Each has 3.13 m^2 of solar panel generating a peak of over 500 W delivered into the four wheel drives embedded in the hubs. A tram, for example, consisting of ten such tram cars would deliver 5 sols of water to the human exploration site each 5 sols. To make a round-trip equal to about one Mars radius out and back would take approximately 100 sols. To be sustained, it would require twenty such tram vehicles in continuous circulation, each with 10 tram cars. Of course it would be desirable if the initial human exploration site were not one Mars radius away from the Rodwell. In this case, one could start with considerably fewer than 20 trams each with 10 cars. But even with a "full complement" of trams and cars, the total dry mass of the trams would be about 23 tons. Adding this to the estimated mass of the Rodwell Drill Vehicle described above and the total landed mass is 28 tons. This is to be compared to the delivery rate of water, at 100 gallons/sol, so it appears that such a system can meet the requirements with a modest mass, such that it is able to deliver water equivalent to the landed mass of the system hardware every ~74 sols of operation. So after 74 sols, break-even on the delivered mass has been reached, and all the water delivered after that is "free" in the sense of not having required new mass be delivered to Mars.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors wish to thank Richard L. Mattingly for suggesting the long chain of tram cars as a method to get a power-efficient water transport without excessive complexity in, especially, backing out of soft terrain. The authors also wish to thank Chad Edwards, Dave Beaty, and Charles Whetsel of the Mars Program Office at JPL for helpful suggestions. Government sponsorship acknowledged.

REFERENCES

1. Wilcox, Brian H. "ATHLETE: Trading Complexity for Mass in Roving Vehicles", proc. IEEE Aerospace Conference, Big Sky, MT, 2-9 March 2013, paper 2570.

2. J.J. Plaut, A. Safaeinili, J.W. Holt, R.J. Phillips, J.W. Head, R. Seu, N.E. Putzig, A. Frigeri, "Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars: radar evidence for mid-latitude Mars ice" Geophys. Res. Lett., 36 (2) (2009), 10.1029/2008GL036379 Figure reprinted with permission 13 Sep 2017 10:41 am.

3. NASA/JPL-Caltech/University of Arizona. - http://hirise.lpl.arizona.edu/ PSP_010625 _2360, Public Domain, https://commons.wikimedia.org/w/index.php?curid=7899284

4. Rapp, Donald, Human Missions to Mars: Enabling Technologies for Exploring the Red Planet, Springer Science & Business Media, 2007, ISBN 3540729399, 9783540729396, Appendix B, Figure B.17. Figure reprinted with permission 23 Aug 2017 11:00 am.

5. See https://science.nasa.gov/science-news/science-at-nasa/2003/09jul_marsdust/

6. Hoffman, Stephen J., Andrews, Alida, Joosten, B. Kent, Watts, Kevin, "A Water Rich Mars Surface Mission Scenario", Proc. IEEE Aerospace Conference, Big Sky, MT, March 2017, paper 2422. Figure reprinted with permission 8 Sep 2017 12:44 pm.

7. Saidi, M. Abardeh, R.H., "Air Pressure Dependence of Natural-Convection Heat Transfer", Proc. World Congress on Engineering 2010 Vol II, WCE 2010, June 30-July 2, 2010, London, U.K., http://www.iaeng.org/publication/WCE2010/WCE2010_pp1444-1447.pdf . Figure reprinted with permission 14 Sep 2017 12:41 am.

8. Rapp, 2007 Appendix B Figure B.14E. Figure reprinted with permission 23 Aug 2017 11:00 am.

9. See http://www.ewp.rpi.edu/hartford/~ernesto/S2006/CHT/Notes/ch03.pdf case 1 page 3.

10. Wilcox 2013

11. The first three values are from an email sent from the late Jake Matijevic to Brian Wilcox, received 20 Oct 2011, available on request. The data for the Apollo lunar rover is from the Apollo 15 and 17 mission reports (https://www.hq.nasa.gov/alsj/a15/ap15mr.pdf and https://www.hq.nasa.gov/alsj/a17/A17_MissionReport.pdf; Apollo 16 data was lost due to a malfunction in the Amp-hour meter on the battery). The Apollo rover power includes the navigation equipment, and so has more in it than mobility power. The CMU Zoe rover estimate is based on Table 1 of the paper "Long-Distance Autonomous Survey and Mapping in the Robotic Investigation of Life in the Atacama Desert" by Wettergreen et al (http://www.ri.cmu.edu/pub_files/ pub4/ wettergreen_david_2008_1/ wettergreen_david_2008_1.pdf) , which gives the power for locomotion as 90-260W, the speed as 0.9 m/s nominal and 1.1 m/s maximum, and the vehicle mass of 198 kg. The power number for Zoe for the nominal case works out to 0.0515 and for the maximum case 0.1487, for an average of 0.100.

12. Wilcox, Brian, Nasif, Annette, and Welch, Rick "Implications of Martian Rock Distributions on Rover Scaling", proc. Planetary Society International Conference on Mobile Planetary Robots and Rover Roundup, Santa Monica CA, 29 Jan - 1 Feb 1997.

13. See http://www.techeblog.com/index.php/tech-gadget/overland-train-is-the-world-s-longest-off-road-vehicle-here-are-5-interesting-facts, where it says "Steering such a train proved to be a serious problem. If the train rounded a corner, the trailers would normally want to even the angles between themselves, forming into a long arc. If there was an obstacle that the driver had avoided, the trailers might eventually hit it as they rounded a corner. To solve this problem, the new trailers were all equipped with steerable wheels. Steering commands were sent from the control cab to each set of wheels in turn, so they started turning at the same point where the driver had. This allowed the train to make sharp right-angle turns, for instance." Presumably this happens because, unlike parking lot trams at large theme parks (where passive linkages steer successive cars very effectively along the path of the tractor), there are significant roll and pitch excursions on rough terrain and the wheels can slip considerably on natural regolith.

BIOGRAPHIES

Brian Wilcox *has been with JPL for more than 34 years. He was the Supervisor of the JPL Robotic Vehicles Group for over 20 years, is now the Manager of Space Robotics Technology, and is a JPL Fellow. He was the Principal Investigator for the NASA ATHLETE and Nanorover robotic vehicle development efforts from 2004-2015 and 1995-2000, respectively. He received a B.S. in Physics and a B.A in Mathematics from the University of California at Santa Barbara and an MS in Electrical Engineering from the University of Southern California.*

A. Scott Howe *is a licensed architect and robotics engineer at NASA's Jet Propulsion Laboratory. He earned PhDs in industrial and manufacturing systems engineering from Hong Kong University and in architecture from University of Michigan. Dr. Howe spent 13 years of practice in Tokyo, Japan, and taught for 6 years at Hong Kong University. He specializes in robotic construction and currently is on the NASA development team building long-duration human habitats for deep space and permanent outposts for the moon and Mars. Dr. Howe is also a member of the JPL All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system development team, and Next Mars Orbiter (NeMO) design team.*